PHYSICS IN INDUSTRY

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PHYSICS IN INDUSTRY

LECTURES DELIVERED BEFORE THE INSTITUTE OF PHYSICS

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VOLUME II

OXFORD UNIVERSITY PRESS
LONDON: HUMPHREY MILFORD
1924

HUMPHREY MILFORD
OXFORD UNIVERSITY PRESS
London Edinburgh Glasgow Copenhagen
New York Toronto Melbourne Cape Town
Bombay Calcutta Madras Shanghai

PRINTED IN GREAT BRITAIN BY MORRISON AND GIBB LTD., EDINBURGH

FOREWORD[1]

THERE seems to be no question as to the complete unity of opinion in regard to the very important value of the physicist to modern industry, which for success is gradually becoming more dependent on Science, the application of science and scientific methods of thought and administration. On the other hand, there may appear to be some lack of allusion in the six lectures that have been delivered to the converse influence which industry and industrial progress has exerted upon science as affording a strong incentive and practical stimulus towards fundamental research.

James Watt, whose great work was in engineering, was by the association of engineering with physics led to discover more about the properties of steam, which were imperfectly known at the time; he had many friends among the physicists and chemists, but their knowledge of the subject in which he was deeply interested did not satisfy him. He therefore experimented himself and drew his own conclusions, which, though approximate only, were yet sufficiently correct to guide him to his epoch-making achievements. He would now probably be described as an engineering physicist. Further, as regards the business side of James Watt, it appears doubtful whether his work would have resulted in great epoch-making results had he not early on entered into partnership with a sympathetic business capitalist—Matthew Boulton. Then again, though less apparent, there can be no doubt that the work of Watt influenced physicists to direct their attention to the accurate determination of the properties and laws of steam—and not long afterwards to the founding of the great laws of thermodynamics. For Joule's great work was in physics, but we find him first trying to improve an electro-magnetic engine worked by the electrolytic consumption of zinc, which he thought would supersede the steam engine of Watt as a prime mover: in this work he showed the skill of the best electrical and mechanical engineer. In this attempt he, however, failed, but his experiments had the result of leading him to the great discovery of the mechanical equivalent of heat, and the absolute zero of temperature, and it would seem probable that, had he not at first attempted an impossible physical and electrical engineering problem, he might never have determined the mechanical equivalent of heat. Again, Sadi Carnot was drawn towards his great work on thermodynamics by watching the Watt steam engines, some of

[1] From the Presidential Address given on 26th May 1924, by the Hon. Sir Charles A. Parsons, K.C.B., LL.D., F.R.S.

which were then working in France, and by pondering on the function of the steam as the working fluid, how it acted within the cylinder, what was the heat cycle, and what was the relation between heat of the fuel burnt under the boiler to the work done. He pondered over these things and eventually evolved the solution, the "Carnot Cycle."

He was not, however, fully aware of the mechanical equivalent of heat or of the absolute zero of temperature. His solution was, in consequence, only approximate, but the accurate solution followed later and the reconciliation of the discoveries of Joule and Carnot was subsequently developed by Clausius, Kelvin, Rankine, and others. Thus were the great and fundamental laws of thermodynamics discovered.

In more recent times the late Lord Armstrong, known chiefly as the introducer and manufacturer of hydraulic machinery and guns, was a physicist in methods of thought and in methods of investigation of engineering problems and principles. He was not a mathematician, but knew well how to direct the mathematical and experimental treatment of a mechanical problem, and of the thermodynamic problems of guns. He was more successful than Whitworth, chiefly because he was a better physicist and had a better faculty for dealing with and applying the fundamental laws of physics. He was an admirable organiser of team work, and an astute man of business with quick observation of the physical conditions of things. On one occasion, by chance, he observed that a tie bar in the roof of the boiler house emitted electric sparks; he found that a leak of steam from an adjacent pipe was playing upon the rod, and that, the rod being of wood, the tie bar became electrically charged. He then carried out experiments and found that jets made of ivory of such a shape as to cause a maximum amount of friction to the issuing steam gave the best results. He thus invented his hydro-electric machine for generating high-tension electricity from saturated steam.

In manufacturing works many years ago, the chief men who owned or controlled them usually conducted such experimental work as was considered necessary, and among them were to be found many good physicists: to mention two instances only—Lord Armstrong, to whom I have alluded, in engineering, and Sir Lowthian Bell in the metallurgy of iron, though many others might be cited in these and other industries.

These men found time for research by delegating routine work to their colleagues or subordinates and were thus enabled to give a portion of their time and undisturbed attention to research on the problems of manufacture and improvements of processes in which they were interested. Though this procedure is still common, there has been a slow but universal tendency in large and even in works of moderate size to establish research departments under and in close collaboration with the management. There may be one or more such departments in touch with each other, in which case they collaborate and afford each other mutual assistance and advice. Equipped with the best instruments and with a highly trained staff they form a component part in the organisation of the works, and are of primary importance in many industries. Care must, however, be taken that there is no loss of collaboration between the management and the research workers, and to this end it is desirable

that the heads themselves should have some training in physics, or evince a due appreciation of the advantages to be derived from research and also have some capacity for directing, and for sympathetic collaboration with, the research workers.

The development of the steam turbine may perhaps be taken as an illustration of a research in one class of engineering, and it may probably also be taken as representative of researches in many other lines of manufacture. At the outset the collection of new data was obviously required before the general line of advance could be determined. Some preliminary experiments were made with high-speed shafts and bearings, but in order to complete these data a small turbine coupled to a high-speed dynamo of primitive design was made. The calculated stresses due to centrifugal force, the laws governing the flow of steam and data from dynamos as approximately known at that time were taken into account. This machine was tested out on very similar lines to those followed by Joule when trying to improve the electro-magnetic engine of Sturgeon. The constants for the flow of steam, the loss by friction in bearings at high surface speeds, the hysteresis and eddy current losses in armature core, conductors, and binding wire at abnormally high speeds were approximately investigated.

Higher mathematics were not employed in this work but were used much later to co-ordinate the accumulated data and forecast the effect of small improvements and refinements which have, in recent years, considerably increased the thermal efficiency of the turbine ; as a matter of fact, it does not now appear that the use of higher mathematics in the earlier stages of development would have been helpful ; the accumulation of sufficiently accurate data to have enabled them to have been practically and usefully applied would have been at that time an additional burthen and hindrance to progress. This, however, does not imply that a mathematical and physical training is not of very great value, for the two men who directed the work had passed mathematical and physical courses at Universities, as well as being trained engineers. All that it is intended to emphasise is that mathematics should be used in its proper place, and, in engineering and pioneer work, chiefly to consolidate the rear, assist the communications, but seldom to lead in the advance. On the other hand, the coming of the steam turbine has had the effect of stimulating research in certain directions, notably in the dynamics of rotating shafts, the law of flow of saturated and superheated steam through jets and the frictional resistances to flow through passages and over surfaces, also to super-cooling and other phenomena.

C. A. PARSONS.

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LECTURE IV

APPLICATIONS OF PHYSICS TO THE CERAMIC INDUSTRIES

DELIVERED IN THE

HALL OF THE INSTITUTION OF ELECTRICAL ENGINEERS, LONDON

ON 9TH MAY 1923

BY

J. W. MELLOR, D.Sc.

PRINCIPAL OF THE CENTRAL SCHOOL OF SCIENCE AND TECHNOLOGY, STOKE-ON-TRENT

SIR J. J. THOMSON, O.M., F.R.S., PRESIDENT INST.P.,

IN THE CHAIR

IV

"THE Applications of Physics to the Ceramic Industries" are so extensive and varied that it is positively embarrassing to attempt to enumerate and explain them in a lecture of an hour's duration. I believe that this remark is applicable to most other industries.

I am so convinced of this that I feel as if I were in the invidious position of a man attempting to explain the obvious, or to clarify what is clear. Indeed, in preparing this lecture, I have several times asked myself if I am not engaged in a hopeless task, *porter de l'eau à la rivière*, in bringing before you some applications of physics to the ceramic industries.

On the other hand, alas, it is rare to find a professional physicist taking his rightful place as part of the organisation of the ceramic industries. To be quite candid, I do not know where to find even one such *rarissima avis*. I would go even further and say that many ceramists do not know what is understood by physics, and probably imagine that it has something to do with medicine.

It would be easy to talk to you a lot of platitudes how greatly physicists are needed to discover and develop the fundamental principles underlying this great industry; it would be easy to convince the bulk of manufacturers that such a proposition is eminently desirable; but without introducing a great many "might be's" it would be difficult to demonstrate that the proposition would be a good investment for his capital. I have never been accused of pessimism, but if statistics of the sister science, chemistry, were taken, I really expect that the probability of a miss would be greater than that of a hit. The so-called fundamental work should be done not for individuals but for all, and all should bear a share of the cost. It is not fair that the cost should be borne by one manufacturer.

The ultra-scarcity of physicists in the ceramic industries may possibly be due to the fact that usually the physicist, and I think also the chemist, trained in the laboratory or academy, and the manufacturer trained in the workshop or counting-house, have quite different standards for testing the truth of a proposition. The professional physicist is proud when he can finish off his particular investigation by showing in parallel columns the agreement of the deductions from his principles with observed facts: the manufacturer tests the success of a particular investigation by counting how much brass, money, the discovery brings into his pocket. This may seem a brutal way of stating facts, but it would be shirking the issue to gloss the truth in more polite language.

We shall not make much progress in bringing the physicist into

closer contact with the industries by sniffing in disdain and claiming that the pursuit of truth for truth's sake is noble and elevating while the pursuit of truth for the sake of money is sordid and degrading. *En passant* I might add that we have only to look around to see that the pursuit of brass, when successful or successfully guised, has the approbation of both scientific and social circles. *Ex hypothesi* the manufacturer is expected to bear the cost of the investigations, and he, trained in the harsh school of beggar-my-neighbour, instinctively asks what rate of interest is likely to accrue from the investment of his capital. It may be difficult for the man trained in an atmosphere of pure truth to realize these different points of view until he has been depolarised. The ethics of the two standards is determined mainly by training and environment. As Seneca would have said: *Gallus in sterquilinio suo plurimum potest* (Every cock crows best on his own dunghill). Each one would have had the other's opinion had training and environment been reversed.

The idea that a man engaged in the pursuit of truth for truth's sake is a superior being working on a superior plane with superior ethical standards, is well illustrated by the recent report of a paper on "Research" by an old friend of mine who occupies an important post in one of our universities. One quotation will suit my immediate purpose: "The history of science reveals the fact that unless research be undertaken with pure motives, it never attains a high level; work undertaken with a view to material advantage of any description is liable to stultify itself and represent in the final balance a very considerable energy-loss."

I do not know what is my friend's definition of "high level," but I assume that by impure motives he means the quest of truth stimulated by the desire for wealth, fame, position, or other personal advantages; and not solely by the pure love of poking his nose into the innards of things. If the statement were true historically or psychologically we should have to adapt ourselves accordingly, but I believe it is all utterly erroneous. I would go further, for I believe, rightly or wrongly, that the direct converse would be nearer the truth. So long as sentiments like that are taught in our universities, we might well despair of getting satisfactorily trained investigators from them. At any rate, the neophytic investigators would have been adequately depolarised before they were in a position to correlate their theoretical work with industrial practice.

Many types of research in industrial work are more difficult, and the results less decisive than the ordinary type of research. The work is more difficult because there is less control of the conditions. In pure science, if we want to ensure freedom from contamination, the work can be conducted in, say, platinum vessels; industrially, platinum cannot be considered, and the work has to be conducted in a vessel made of firebricks. I once counted between sixty and seventy improvements in an industrial process which had been patented, and which had proved abortive, not because of any intrinsic weakness in the method, but because wear and tear on the containing vessels at the working temperature was

too great. I have also reported adversely on many a process solely on these grounds.

The applications of ideas obtained from small scale experiments frequently prove abortive when applied on a large scale, and it is common to hear that "experiments made on a small scale end in smoke when tried on a large scale." This means nothing more than that the small scale experiments are carried out under specified conditions well under control, while those on a large scale are usually made under quite different conditions. Given the same conditions in the two cases, we have faith enough to believe that the same results will follow. In passing from one to the other it is often necessary to take that leap in the dark represented by what the physicist calls extrapolation. It is necessary to spare no pains in realizing the working conditions before the attempt is made to apply the laboratory results on a big scale.

Every branch of physics—heat, sound, light, electricity and magnetism, statics, dynamics, and hydrostatics—has applications in the ceramic industry.

In order to bring my subject within manageable limits, I have decided to eliminate applications of physics which are common to other industries. By the courtesy of your secretary, Mr. Spiers, I was able to read the lectures by Sir J. A. Ewing and Mr. C. C. Paterson. Much of what is said there applies also to the Ceramic Industries. When this course of lectures is completed, I expect the Committee will find that the different industries are linked together by many bonds. A manufacturer is sometimes delighted to find that when visiting by chance the factories of a totally different industry, there is at work a machine which he can quickly adapt to his own industry with very beneficial results.

After eliminating these common factors, which might be made the subject of a separate lecture, the residuum left for me now has the character of mosaic tiling. It is a collection of miscellaneous applications of physics.

Perhaps some will think I am romancing a little to speak of the applications of sound. In the "Question Box" of the Ceramic Society, not long ago there was a query, "Is the sounding of a piece of pottery a logical test of its degree of firing?" and in the firebrick industry the relation between the sound and the quality of the goods might reasonably be raised. Both maker and user like to hear a good sonorous ring when two bricks are struck together. Other things being equal, it is certainly a very rough indication of the progress of vitrification, and I have seen men rejecting or accepting deliveries of firebricks for coke-oven work solely on the ring of the individual bricks when struck with a hammer. I am inclined to think that too much stress is laid on the ring as a general test because silica bricks made with precalcined quartz in the ordinary way usually have a poor leaden ring; but who dare say that the bricks are better or worse than those made in the usual way? However, I suppose some one will say that there are similar degrees of sonorousness even with the bricks with a "poor leaden ring."

The applications of light, particularly in connection with colour, are numerous and varied. The work of physicists on the production of a

mode of illumination to imitate natural light is being followed with keen interest. The matching of coloured glazes, etc., in artificial illumination is difficult; sometimes impossible. The effect of different modes of illumination is not very marked with, say, the copper-blue colours; but artificial light always causes the cobalt-blue colours to appear darker in tint. One good test of the true copper turquoise or Persian blue for those whose eyes have not been adequately trained to distinguish it from the imitation cobalt matt blue is to watch if there appears to be a deepening of the tint in artificial light. Then there are some interesting chrome colours which appear green in daylight and crimson, pink, or purple in gaslight or electric light. Not many years ago I sent a nickel-blue tile to have a coloured block made in imitation of the tint. I returned the block which was sent, and remarked that the block-maker must be colour-blind, his imitation was green. He gave the *tu quoque* argument, saying the colour *was* green. To make sure I asked a room of people if the colour of the tile was blue or green, and all said blue. By accident I found the blockmaker was right in daylight, and that I was right in gaslight.

During the War, when the Zeppelin raids were menacing, blue lamp-bulbs were needed. Nothing seemed easier than to add half a dozen per cent. of cobalt oxide to the batch. When this was done, the glow of the red filament through the glass led a short-sighted man to mistake the blue for red. The addition of copper oxide with the idea of masking the red by its complementary green did no good; but when chromic oxide was added, the red colour was no longer troublesome. Observations on the absorption spectra showed at once the reason why copper oxide failed and chromic oxide succeeded. Had absorption spectra of those oxides been available, I dare say some of you would say that a man would have been a fool to expect copper oxide to be effective. This shows that such industrially useless observations as the absorption spectra of colouring oxides in glasses would have been a valuable asset to the manufacturer, and would have saved in one single case far more money than the cost of the investigations. The very simple illustration I have quoted will recall the very skilful and ingenious work which has been done in the preparation of glasses with particular properties exaggerated, *e.g.* high refractive indices, opacity or translucency to particular parts of the spectrum, etc.

There is an extraordinary large number of applications of surface-tension and capillarity. The relationship between "Soap-bubbles and Pottery," or between "Soap-bubbles and Firebricks," may seem exceedingly remote. In reality, the phenomena connected with surface-tension exhibited so well by soap-bubbles apply to many problems connected with the behaviour of bodies during the drying and firing; and these can be understood in a restricted way only by reference to soap-bubble phenomena. The favoured lines of attack on refractories by molten slags are usually connected with capillary action.

I think many silica brick manufacturers would be happier men if the physicists had never devised methods for measuring the indices of refraction of small crystals. I allude to those who wonder what on earth

is meant by those who talk glibly of α and β tridymite or cristobalite. Without the work of the physicists some of us would be very puzzled with the extraordinary changes which occur during the manufacture and use of these materials. We are still confronted with many puzzles, but some of those manufacturers who specialise in tridymite or cristobalite bricks would have been still in the old rut had the physicists not spent good time and good money on what appeared at the time to be work with no utilitarian purpose.

Sir William Bragg's work on X-ray spectra promises in a few weeks to do for the firebrick manufacturer what the index of refraction has done for the silica brick manufacturer. The application of chemical methods to elucidate what happens when clays are heated led us into a cul-de-sac. The index of refraction left the problem unsolved. A preliminary survey of the X-ray method was so encouraging that I am sanguine enough to believe another item will shortly be added to the long list of obligations which the ceramic industry owes to the physicist.

The applications of magnetism have been partially explored. The main problem involves the separation of particles of metallic iron from clay slip—that is a kind of slurry with powdered clays, etc., suspended in water. The use of a train of horseshoe magnets is giving way largely to systems with electro-magnets like that used by the Rapid Magnetting Company, which is arranged to prevent the passage of the dirty slip into the purified slip if the electro-magnets cease to work. This machine with reasonable care does its work very well. There is also a marked improvement in efficiency.

There is an unsolved problem involved in removing particles of cupriferous pyrites from fireclays used in making certain types of sanitary goods like baths, urinals, etc. There are machines in which a stream of powdered material is passed through an intense magnetic field when feebly magnetic minerals like limonite, hæmatite, chromite, pyrites, etc., are deflected from the main stream and a separation is effected. Attempts to separate cupriferous pyrites from clays in the electro-magnetic separators used in concentrating ores for metallurgical purposes have not been successful. A similar remark applies to the electro-static separators.

The problems of heat are numerous and varied. All the products of the ceramic industries have to pass the ordeal of fire. In some factories making the best of wares, where everything is sacrificed for quality, I estimate that about 2 per cent. of fuel is spent in firing the biscuit ware, and the remaining 98 per cent. of fuel is a dead charge against the oven saggars, etc. At the other end of the scale, say in firing building bricks, the processes are much more efficient and economical.

There are scores of problems involved in the firing which would serve as a delightful hunting-ground for the physicist. The graveyard of lost hopes, the Patent Office records, is packed with abortive improvements. Any drastic improvement is bound to have a severe struggle for existence. Complicated systems of flues and screens in the hotter parts of the furnaces are not usually a good recommendation when one attempts to picture their condition after, say, a six months' run. There

is also the experience of the workmen to consider. They manage routine operations with a wonderful skill; but directly the conditions are changed, they are often helpless and without resource. They are not quick to adapt their traditional skill to new operations; and often not willing to try. Outsiders often wonder at the hysteresis, or passive resistance offered by these industries to drastic changes; they forget that such changes may mean scrapping the traditional experience of generations of the workmen. In an exceedingly specialised industry it is difficult to foresee what effect a change at one stage of the work will have on subsequent operations. The effect of a change at A in a long sequence of operations, ABC . . ., may produce disastrous results at the XYZ stages.

The drying of clays and clay wares presents a fine series of problems. In a block of clay there is an evaporation of water from the surface. New supplies are brought to the surface by the redistribution of water in the capillary pores. This is at first attended by a contraction of the clay. If the evaporation of water from the surface is faster than the passage of new supplies from the interior, there will be a greater contraction near the surface than in the interior, and strains will be set up and cracking is likely to result. Similar results occur when the drying is faster on one side than another. The isohydric curves in the drying mass of wet clay probably have a close analogy with the isothermal lines in a cooling body. While Fourier's analysis is applicable to the latter, there are complications with the former. For instance, during the first stage of the drying, the cubical contraction is equal to the volume of water lost; in the second stage, the contraction is less than the volume of water lost; and in the final stage, water is lost without any appreciable contraction. The distribution of water in the interior of the drying mass of clay will have to be worked out by the physicist. There are exceedingly important practical applications: (1) because of the losses which ensue owing to the development of drying cracks; and (2) because an inordinately long time is needed to dry large masses without the development of these cracks. There would be a direct saving if this time could be safely abbreviated.

The physicist will also have to work out the relation between the surface of the drying solid and the humidity of the surrounding atmosphere. We have the so-called humidity dryers in which the drying is speeded up by raising the temperature and keeping the atmosphere fairly humid. This accelerates the movements of the water in the interior of the clay, and in the ideal case the humidity of the atmosphere must be so regulated that the speed of evaporation of the water is almost balanced by the speed of distribution of the water in the interior of the mass. The drying then proceeds without introducing undue contraction strains.

Professor Lees is studying the thermal strains in what might be called monolithic kilns. When he has settled that subject satisfactorily he will strip off some of the (at present) necessary assumptions and approach more nearly to actual kilns. Meanwhile I hope he will be enticed along another path, and pass from thermal strains to what I

believe is a far more troublesome subject, virtually untouched. I allude to what might be called *contraction strains*. These are of two kinds: (1) strains set up during the drying or rather the uneven drying of special shapes; (2) strains set up during the firing of special shapes. I expect that the same general rules will apply to the thermal strains, to the drying contraction strains, and to the firing contraction strains. He will show us how it comes about that, when a circular plaque spontaneously breaks, the fracture is usually directed to the centre, while with an oval plaque the cracks may be directed towards either or both of the two foci of an ellipse. He will further show us how it is safest to dry some annular shapes with an auxiliary core which can be removed when the piece is dried. He will also be able to tell the designer of chemical apparatus, furnaces, coke ovens, sanitary goods, etc., that the strains set up during the drying, firing, and subsequent use of certain shapes are too dangerous to give a satisfactory working margin of safety. The designer of furnaces and the like will then realise that the question he should put to the manufacturer is not, " Can you make these special shapes ? " but rather, " Are any of these special shapes likely to have a dangerously narrow margin of safety in manufacture and use ? " He should then consider the possibility of modifying his design so as to eliminate shapes liable to be dangerously strained. The experienced manufacturer's instinct is generally a fairly good guide. To-day the designer generally considers the manufacturer's objections to be a preliminary manœuvre to raise the prices, or a reflection on the manufacturer's skill; and he pooh-poohs any suggestions the manufacturer might make in this connection. The more I see, the more I am convinced that it is the user who pays for the designer's fallibility.

There are interesting problems connected with the grain of clay. It seems as if the particles can be oriented differently so that the drying and firing contractions of the mass are different in different directions. A circular bat of wet clay, for example, may contract to form an elliptical slab. When some clays pass through a long-nosed pug-mill, a slab cut in the direction of motion has a greater percentage contraction than when taken at right angles thereto. At first I thought it was due to wetter clay accumulating near the axis of the direction of motion. I now think, if possible, that in passing along, the flatter particles have a tendency to travel broad-side, not edgewise; much the same as a shilling would sink in still water with the flat side downwards. This would give a greater number of wet surfaces per cm. in the direction of motion than at right angles thereto; an almost analogous case has been worked out in hydrostatics.

Again, if there is any distortion during the drying of wet bats of clay, the bat can be straightened by damping it and drying it under pressure; but in the subsequent contraction which occurs during the firing, the particles continue contracting along the old paths, and the slab becomes distorted in a similar way to what it was after the first drying.

I mention these facts simply to show that the physicists have yet to till a field of virgin soil. We know very little about the hydrostatics

and dynamics of liquids with an indefinitely large number of particles in suspension. Mr. Ackermann has made a start. This subject too is connected with the plasticity of clays; this property is fundamental. In the ceramic industries I would say that without that quality clays would not be clays and the fictile arts would be sometimes very different from what they are.

I am not going to discuss the applications of electricity as a source of heat in the testing furnaces. After nearly twenty years' use of these we wonder how ever we could do without them. For high temperature work they are simply invaluable. I have not come across any electric furnaces likely to give satisfactory results in firing pottery; though for crucible work, melting glasses, frits, and the like, the results are quite satisfactory and would come into more general use if the power were cheaper. My friend, Mr. Odelberg of Sweden, is designing a kiln to be electrically heated. I have predicted that there will be curious problems connected with the effects of convection currents of hot air. With gas or coal firing the heat is carried and distributed in the furnace largely by the currents of burning gas accompanied by a large excess of hot air. With electrical heating there is a radiation of heat from the hot walls, and also convection currents set up owing to differences in temperature in different parts of the furnace. The effectiveness of convective heating depends on the mode of setting the goods to be fired. If the setting be such as to baffle the convective currents, the heating in large kilns is usually too local, and in consequence there is too much difference of temperature between the different parts of the furnace. I am inclined to think that with the electrical heating of a large chamber there would have to be a subsidiary mechanism to ensure the better circulation of gas so as to get good convective heating.

There are some important physical problems connected with the glazing of pottery. It will be obvious that in the ideal case the coefficient of thermal expansion of glaze and body should be the same. If in cooling the glaze were to contract faster than the body, the glaze would have a tendency to craze; and conversely, if the body were to contract faster than the glaze, the glaze would tend to chip or peel. Some years ago a large number of measurements of the coefficients of expansion of different glazes and bodies were made in France; and a great quantity of data has been piled up in connection with glasses. I never heard that the results were of much practical value in adapting glazes to bodies. In fact, some of the results contradict experience. This does not mean that the physical measurements of the expansion coefficients are of no value, but it does mean that the adjustment of glaze and body is much more complex than has been assumed, and that enough measurements have not been made. There is the tensile strength of the glaze to be considered; also the rate at which the glaze attacks the body, and the effect of a solution of the body in the glaze on the coefficient of expansion of the glaze.

As I read it, the measurements made for the French potters have served a very useful purpose in demonstrating the complexity of the phenomenon under discussion. It is wrong to say that the measure-

ments of the coefficients of expansion are useless; rather do they want repeating and the results correlated with measurements of other vitally important factors.

The curious after-effects observed by physicists in connection with the elasticity and thermal expansion of glazes have enabled potters to understand qualitatively what appeared to be a very mysterious behaviour of glazes. I hope that quantitative data will be available in due time, and then we shall be able to predict without any misgivings the future behaviour of particular glazes.

For reasons previously indicated, I have not discussed the more obtrusive application of physics which the ceramic industries share in common with many other industries; nor have I made more than passing allusions to cases where materials are required to satisfy certain specific tests such as the thermal and optical properties of glasses, and the breakdown voltages of electrical insulators, sparking plugs. etc. In cases like these, the ceramist must proceed step by step with the physicist. I have rather picked out a few cases intended to show that in some instances time and money would have been saved had certain physical data been available at the time they were needed, and a number of rather out-of-the-way problems which will sooner or later have to be solved by the physicist.

The processes in the ceramic industries are so complex that I do not know whether physics or chemistry is of the greater importance, but I do know that both together are indispensable. Chemistry without physics would be a poor subject. Indeed, as I read it, chemistry without physics would be purely descriptive, much like descriptive mineralogy. The invasion of physics has prevented chemistry from developing into an elaborate collection of recipes after the style of a cookery book. The points of contact are said to belong to physical chemistry; physics, or if you like, physical chemistry, is busy revolutionising inorganic and organic chemistry. I have great faith that physics will do equally good work in ceramics.

LECTURE V

THE PHYSICIST IN THE TEXTILE INDUSTRIES

DELIVERED IN THE

HALL OF THE INSTITUTION OF ELECTRICAL ENGINEERS, LONDON

ON 22ND OCTOBER 1923

BY

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The Hon. Sir CHARLES A. PARSONS, K.C.B., LL.D., F.R.S., President Inst.P., in the chair

V

THE building up of the textile industries has been one of the greatest factors in civilisation, yet it has been said that the great weakness of the cotton industry—and this applies equally to the other textile industries—is that it is not using to the full the immense powers bestowed on this generation by scientific discovery. The four preceding lectures on "Physics in Industry" have convinced even the most dubious minds of the inseparable bonds linking the purest physical science with applied science as it is known to the industries, and no further effort on my part is needed to vindicate how closely wedded are the subjects of physics and engineering. To quote Sir Michael Sadler: "Applied science was nobly defined in the charter granted in 1828 to the Institution of Civil Engineers as 'The art of directing the great sources of power in nature for the use and convenience of man.' Applied science derives most of its strength from pure science, pure science a part (though only a part) of its vindication and encouragement from applied. The difference between them is less one of subject-matter than of motive. Either isolated from the other is weakened through lack of contact with the characteristic virtues of its opposite. Both may form part of the life-work of a single investigator. In both the universities should participate, because it is the function of universities at one and the same time to widen the boundaries of knowledge and to show how knowledge can be used for the welfare of mankind."

When first I elected to do textile research work I confess that I was doubtful if the field of research was at all bright for the physicist, but immediately after my first visit to a cotton-mill the vista presented to me was full of promise. Though the production of textile fabrics is, next to food, the greatest necessity of mankind, and though all of us have at times admired the beautiful materials displayed in shop windows, I suppose but few of you here have had the privilege of visiting a spinning-mill or weaving-shed, and there tracing the numerous processes through which a substance like cotton passes from the raw state, as it is seen in the Liverpool docks, to the finished fabric ready for making into garments or for adorning our homes. Those of you who have had this opportunity will have been astonished at the wonderful perfection and delicacy of the machinery employed, and will have admired the supreme engineering skill with which the raw material is handled. Perfection of manipulation seems, at first glance, to have been attained. One might say that if such skill can be developed in the past without the aid of the physicist then there is no need for him, and this no doubt is the attitude of some people whose conservatism still holds them members of the "rule of

thumb " or " trial and error " school. One cannot help but look with admiration upon what has been achieved by such methods, but at the same time one cannot help but wonder what advantages might have been gained had the great skill of the operative been united with the insight of a trained scientific mind.

For example, if one tries to probe the inner functions of any of the complicated, or for that matter even the simpler machines, one soon finds how little is really known about the treatment to which the material is being subjected. On inquiry, varieties of explanation are offered, each no doubt a carefully weighed opinion, but still, only an opinion. The reason is that many such investigations that have hitherto been made took place under vaguely defined and, therefore, unscientific conditions, with the result that other experimenters, equally unscientific, have sworn to contrary views and valuable time has been wasted. Might not the application of more scientific methods settle such controversial matters and possibly in the end lead to improved machines? There is no question of decrying the ability of the skilled operative; his skill based upon ten, twenty, or fifty years' mill experience can never be attained by a man whose younger years have been spent in training as a scientist. Undoubtedly the physicist's duties are complementary to those of the operative.

Here lies the opportunity of the physicist—to bring scientific method into the testing-rooms and even into the mill in order to ensure that tests made upon the various products of the different machines shall be comparable with those obtained at other times, either on the same or similar machines. As I hope to show later, the textile industries offer an almost entirely unexplored field for the research physicist, and indeed, in my own case, it very soon became apparent that it was not a question of searching for a problem worthy of investigation, as I had at first thought it might be, but one of selecting, from the great number of attractive problems presented, a few which should form the most reliable basis on which to build a secure foundation for the development of a progressive research programme. It should be remembered that physical research in the textile world is by no means in such an advanced state as it is in the metallurgical world. Indeed, it would be possible to count the number of physicists, at present engaged in England on textile research, on one's fingers with perhaps a little assistance from one's toes. A brigade of trained physicists would be more in proportion to the problems urgently awaiting solution. I think it safe to say that there is no other industry so much in need of co-operation with the physicist as is the textile group.

As an illustration of what I have said I should like to quote the following remarks of a practical spinner relating to what is accepted to be the most important machine in spinning, called the carding engine. I hope I may be forgiven for bringing in unfamiliar technical terms, but even if these are not understood I think you will appreciate the point I wish to make.

" In carded yarns there are too many motes and neps. Careful carding does not eliminate these faults but keeps them within reasonable bounds. Expert carding masters are putting forth great efforts to im-

prove the carding engine.) The speed of the fundamentals of a carding engine—cylinder, doffer, flats, and taker-in—have been varied indefinitely. The kind of wire, the counts, settings, the manner of grinding have all been subjected to experiment. The convictions produced in our minds by these successive experiments are legacies which it would be unwise to revoke; but as scientists you will take nothing for granted, and you others as practical men will seize upon theories and put them to a rigid test. Inventors from Daniel Bourne, in 1748, to Harry Walsh, of recent years, not forgetting those giants, Paul, Arkwright, and Evan Leigh, have tried every conceivable way to make the carding engine a finished machine. The machinists and pioneers tried to work carding engines with movable and stationary flats, with rollers and clearers, with combinations of all these, with flats on top and flats underneath, with flats working forwards and backwards; some have even tried to make them work without flats or rollers. In the matter of card wire, we have iron wire, mild steel wire, hardened and tempered steel wire, each and all with the tooth mostly in vogue at the particular period. We have had chisel ground, round points, plough ground, side ground, and maybe others. *And yet, to-day, whilst the carding engine is indispensable, it is a failure.*" Can the physicist, by systematic research, applying the scientific method, help in such a case as this? I think so.

There is one outstanding factor which must here be brought to the notice of the physicist contemplating textile research, and this applies to textile materials in general, including cotton, wool, flax, and, to a less extent, silk. The material he has to investigate is generally most disturbing in its variability. The result is that a very careful selection or sampling of the test specimens must be made, and in many cases very laborious series of tests are needed before a result representative of the bulk, which is the only material recognised by the manufacturer, can be obtained. Series of observations involving sometimes several thousands of readings have to be taken and conclusions drawn from them by statistical methods. *I think that this is really the keynote of my lecture; it differentiates rather sharply the work of the research physicist in the textile industries from that of the research physicist in such industries as mechanical and electrical engineering.*

It is quite impossible in the time at my disposal to give you an idea of the sequence of machines involved in the production of a thread or fabric, but I have thought that by showing you samples of cotton in its various stages of manufacture, and by concentrating on this raw textile material, it would be possible to give you a better understanding of the physical problems that will be put before you later on. As regards the nature of the spinning and manufacturing processes, the cotton, woollen, and linen industries have many points in common, and the physical tests I shall describe apply, with minor exceptions, to all textile materials. I am quite aware that this is a departure from the plan followed by the previous lecturers, but I think that the strangeness of the material demands such a preliminary explanation.

After the flowering of the cotton plant, the boll appears, and as this opens we see the fibres sticking out from the seeds as a sort of fluff. These

fibres are the raw material from which all cotton goods are made. Seventy-eight millions of the single fibres weigh one pound. I am afraid that if I hold up one of the single fibres, you will not be able to see it, but Fig. 1 shows a photograph of a fibre under high magnification. You will see that it is like a twisted bull-headed rail. As regards section, the fibres show complicated shapes as indicated in Fig. 2. This is the raw material with which the physicist has to work, and you will realise how complicated our test specimens are. After the cotton has been picked, it is subjected to a process, called ginning, which removes the greater part of the seed and dirt, and it is next put into bales under considerable pressure and shipped to the mills. The bales after being opened by machinery are formed into laps which are next passed through what is called a carding engine, and the cotton comes out of the machine in the form of a long continuous rope or sliver. Next, these are grouped, usually six together, and passed through a series of frames known as draw frames, and, although you do not notice any appreciable difference between the products, there is (1) a complete mixing of the cotton; (2) a gradually increasing regularity as measured by the weight per unit length; and (3) a greater degree of parallelisation of the individual fibres. From this final rope or sliver a thread similar to, but not identical with, the one you are familiar with in ordinary sewing cotton is produced by a series of processes wherein the cotton rope is by stages gradually extended and twisted. The machines in which this is done are known as slubbing, intermediate, roving, and spinning frames. The last carries out the final spinning process: there are two kinds of spinning: (1) called mule spinning, intermittent in mechanism, giving the thread wound in the form of a cop; and (2) the ring-frame, continuous in mechanism, giving the thread wound on a bobbin.

Such threads may now be dyed and doubled together, forming plain and fancy yarns; sometimes four or six threads are folded together to give the familiar sewing cotton.

At this stage I should like to give you some examples of the types of physical research on which we have been engaged. The behaviour of twisted textile fibres such as you have seen is of fundamental significance in technology. Though the fibre is so minute, its rigidity may be readily measured with all the precision which is justified by the extraordinary irregularity of this material, by using a small torsion pendulum. In a series of observations on various cottons, the mean couple for one twist per cm. varied from 0·01 dynes cm.^{2} in the finest Sea-Island to 0·111 in the coarsest Indian. The effect of such great variation is evident in the appearance and feel of yarns made from different grades of cotton and necessitates an empirical adjustment of twist in the spinning process. These measurements also attract attention, by the marked correlation between the length of a fibre and its rigidity, to a certain tendency towards a constant fibre weight which may simplify the study of the effects of breeding and environment on the cotton lint.

The modulus of rigidity was calculated from observations on certain fibres which approximated to circular rods, giving a value of $0{\cdot}23 \times 10^{11}$ dynes/cm.^{2}; about 1/30 that of steel. Using this, the observed rigidity

PLATE I.

FIG. 1
Cotton fibre

FIG. 2.
Cotton fibres (sections).

[Face p. 28.]

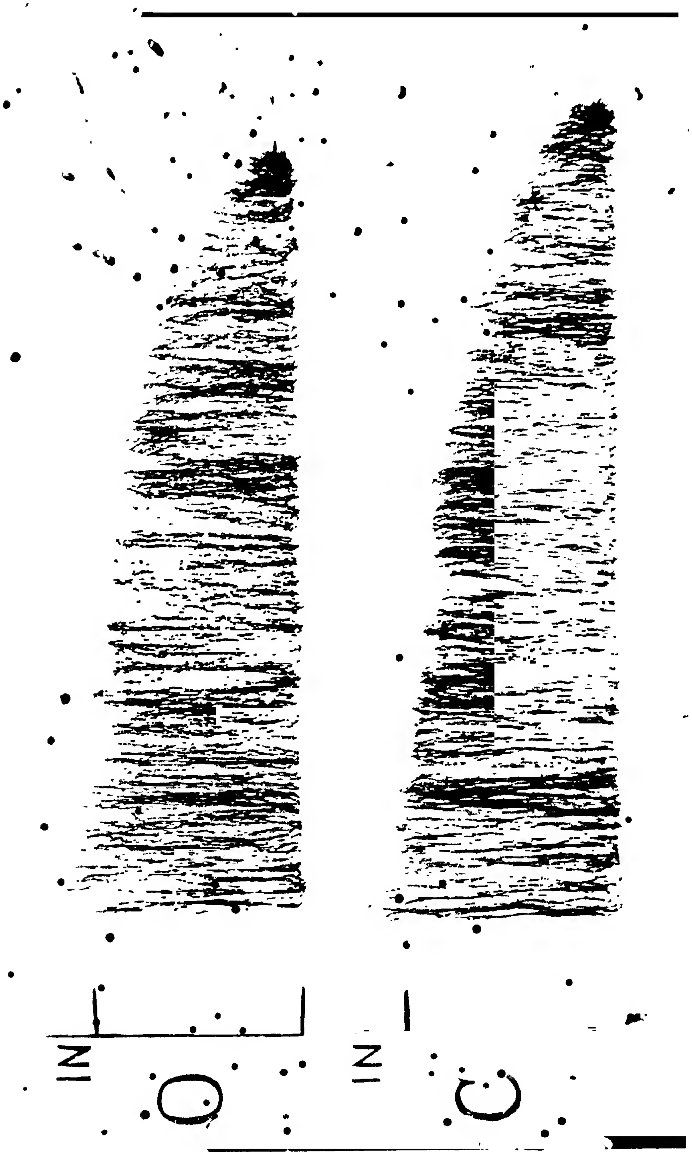

FIG. 3

Analysis of fibres in cotton samples

O = Fibres from ordinary low draft yarn C = Fibres from Casablancas high draft yarn

[Face p. 29.

and cross-section of a variety yield a measure of the effective configuration, the degree of secondary thickening and of wall collapse, which differs from variety to variety.

The elastic properties under strains of some duration are of even greater interest technologically and scientifically. In order to have one definite method of expressing and comparing elastic imperfection, the decrease of couple with time under constant twist was observed by deflection of a small magnet suspended in a controllable field. The curves obtained closely follow an exponential law giving three quantities to describe the whole behaviour, viz. the initial couple, the elastic couple which persists under strains of long duration, and a time coefficient which measures the rate of decrease of the plastic component. The constants which were given by different textile fibres express very well the various qualities of these materials otherwise only described by such vague terms as springiness, limpness, feel, hang, sagging, etc. The effect of any treatment and of humidity conditions may be studied in this way for any of the textile raw materials, and the bearing of such work on spinning and finishing is obvious.

The next point I should like to bring before you is the method of analysis adopted in order to trace the quality of the cotton at each stage of the spinning process. As the cotton passes through the various machines it is possible that some of the fibres get broken, and it is important to know to what extent such damage takes place. Two methods of analysing the sample are used : (1) in which the fibres are laid down longitudinally in the order of their staple lengths (Balls' Sledge Sorter) ; (2) in which the fibres are laid down laterally in the same order (Baer Sorter).

The second uses a series of wire combs through which the sample of cotton is drawn. By suitably manipulating the machine the fibres are drawn out in small tufts and laid side by side on a plush-covered plate as shown in Fig. 3. You will see that there is a very great variability of the length of the fibres, a comparatively few very long ones and a large number of medium ones and some very short ones. If we select length intervals of 1/8″ or 1/16″ it is possible to collect the fibres whose lengths lie in such limits and plot their weights, obtained on a micro-balance, as a frequency diagram, and from such a diagram to deduce the most frequent fibre length (result obtained more readily by the Sledge Sorter). It is possible by such means as I have briefly indicated to see what damage, if any, is done to the cotton by any given machine. The process is a laborious one, but the results are of great value and interest to the spinner. For example, the two arrays of fibres shown in Fig. 3 are obtained from yarns which have been spun by two different processes, one (C) involving a high [illegible] draft, missing out one of the usual frames, while the other (O) has the normal draft using all the frames. Though it was generally supposed that the former was more likely to break the fibres the analyses indicated that such was not the case.

One of the most important qualities of a spun thread, particularly those used for the manufacture of the finer fabrics such as voiles and poplins, is what the spinner terms the " evenness " or regularity of the

thread. Hitherto his test has been the somewhat primitive one of winding the thread on a dull black surface and judging its merits by the visual patchiness presented. A quantitative measure of regularity has only recently been devised. This is a definite physical measurement which has not only standardised regularity quantitatively but has disclosed important defects in the modern methods of spinning.

The thread Y to be tested is drawn between a pair of case-hardened steel shoes, S_1 and S_2 (Fig. 4), the bottom one, which is mounted eccentric-

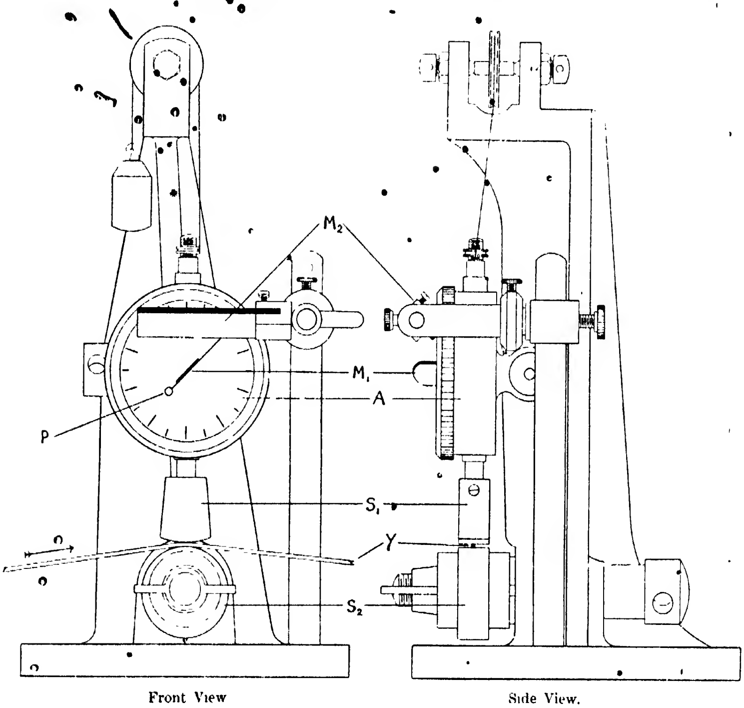

FIG. 4.

Indicator for measuring regularity of yarns.

ally, being fixed while the top one rides on the upper surface of the thread and rises or falls according as the element of thread between the shoes has a high or low twist, the more highly twisted elements being the less compressible. The top shoe is connected to a sensitive indicator A, and a pointer P on this carries a mirror M_1, which reflects a beam of light upwards to a fixed mirror M_2, and then outwards towards the reader, and is received on a strip of bromide paper mounted in a camera not shown. The motor mechanism which draws the thread between the shoes drives the bromide paper through the camera at an exactly proportionate rate.

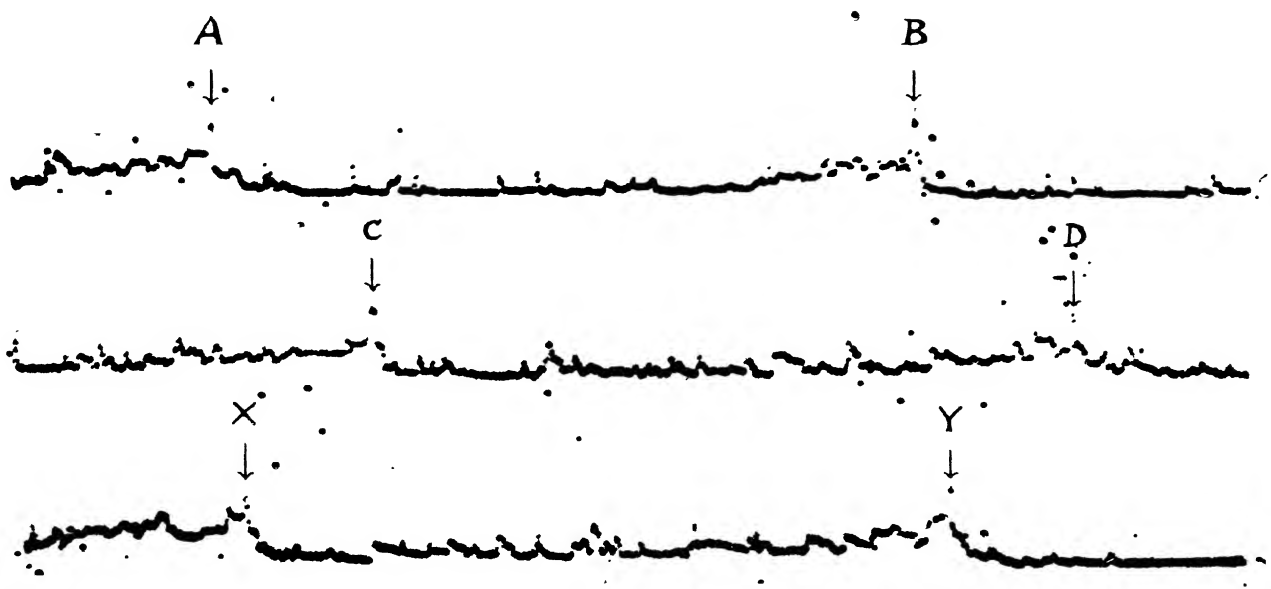

FIG. 5.
Regularity of mule yarn (100's) showing periodic hardness of twist corresponding to stretch of mule
AB = CD = XY = 65".

[Face p. 31.

As the thread slides through the shoes the beam of light oscillates from left to right, and since the bromide paper is travelling vertically downwards, the beam traces a path on the paper showing continuously how the twist hardness varies along the thread.

Fig. 5 shows such a trace for a thread spun on a mule. The slopes of the trace are increased 18,000 times. Direct evidence of a periodicity of twist is indicated, and this has been interpreted in terms of the intermittent action of the mule mechanism, which is far too complicated a subject to be discussed here. I might point out that in England there are 40,000,000 mule spindles against a total of 57,000,000 in the whole world, and if by further study even a slight improvement of this method of spinning can be made, this application of physical research will have fully justified itself. There is an inverse correspondence between the twist and visual thread diameter, the thread appearing thin where the twist is high and *vice versa*. The importance of analysing these effects is realised in the subsequent process of weaving the thread into a fabric, for if the width of the loom corresponds to the interval of periodicity mentioned one is liable to get a streaky fabric, and the streakiness is clearly visible in the plain or dyed material. Similar effects may arise in the knitting of hosiery goods, a barred or blotchy fabric resulting from the irregularities in the variation of twist.

Threads spun on what is called a ring frame, an alternative machine to the mule, show only non-periodic variations of twist hardness in keeping with the continuous nature of the ring-spinning process. Such variations as do exist are determined by variations in the regularity of the roving from which the final thread is spun, and irregularities of this type are more liable to occur in ring than in mule yarns. As a further example of this method, numerous comparative tests of high and low draft yarns have been made, and measurements from the photographs, when treated statistically, enable us to compare the regularity of any high and low draft yarns, and hence the merits of the systems.

The plain, doubled, dyed, or fancy yarns may be woven into an amazingly large variety of fabrics, with the appearance of which most of you are familiar. In order to make my description complete it will be necessary to call your attention to a simple type of loom (Fig. 6). The threads which are to constitute the warp of the fabric are wound on a beam A and placed at the rear of the loom. Two thousand or more such threads are drawn intermittently through the machine in a direction indicated by the heavy dotted lines. B and C are what are known as healds, which separate the plane of threads into two sheets, and, as the healds lift up or let fall their respective sheets periodically, the shuttle carrying the weft thread flies through the parted warp threads, and the interlaced warp and weft form the fabric. I have given only a very rough outline of the weaving process, but you will, I think, notice that the threads are subjected to periodic stresses and strains. Sometimes the threads break in the process, and it is important to examine the behaviour of textile threads under stresses approximating to those involved during weaving.

As an illustration of the application of a physical test to the effects

of oscillating tensions on threads, the machine shown in Fig. 7 may be of interest. The threads are mounted in grips as shown, and they are subjected to a variable load determined by the static load and the speed and amplitude of the rotating cranks at the top of the machine. Loss of twist is prevented by the bifilar suspension of the load as shown. It is found that although the maximum load to which the thread is subjected never attains the ordinary breaking load of the specimen, yet all

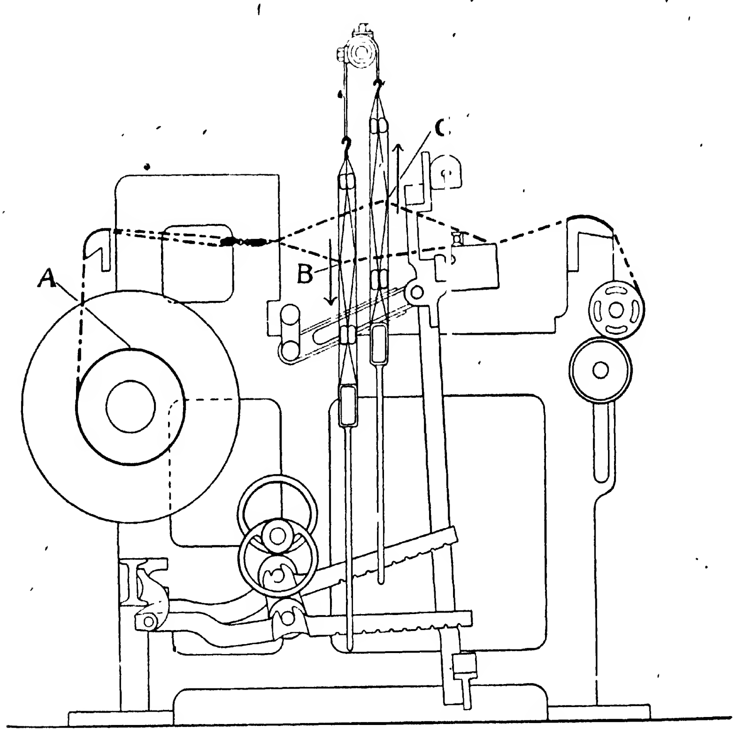

FIG. 6.
Plain loom, showing motions of warp threads.

the specimens can be broken by applying a sufficient number of oscillations. Such breaks are due to minute accumulative permanent sets which occur for each oscillation, the fibres slipping slightly each time the load passes through a maximum. An interesting confirmation of the periodic variation of twist in mule threads is shown in Fig. 8. Each peak corresponds to a peak in the photographs shown in Fig. 5, and it is seen that although some of the specimens break under a few hundred oscillations the high twisted specimens do not break under 5000 oscilla-

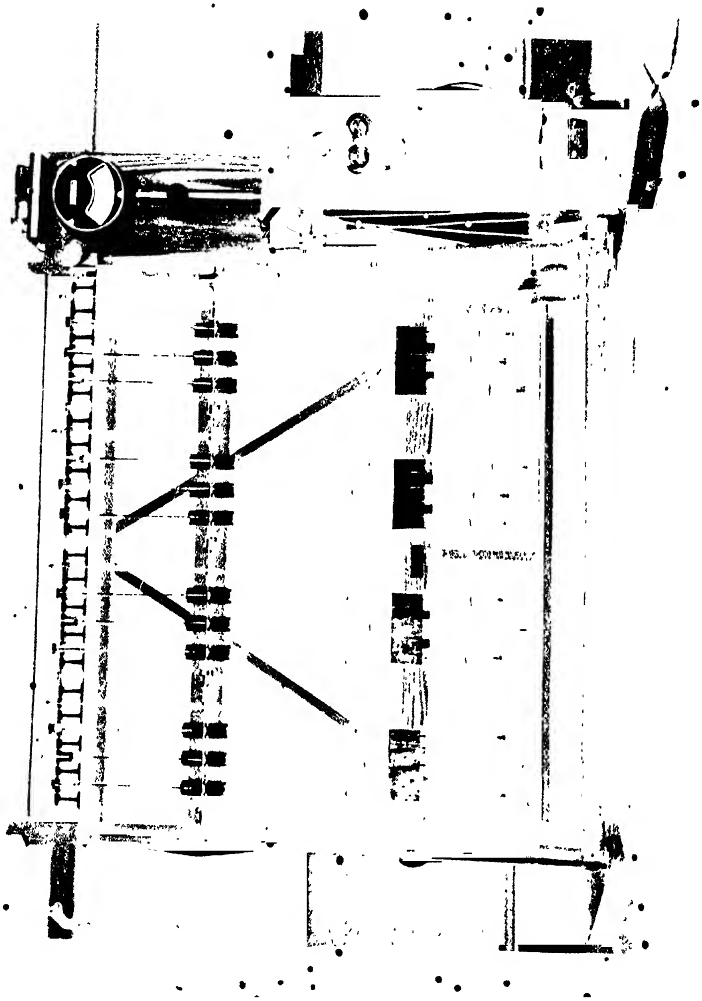

FIG. 7.

Oscillating stress tester for applying periodic loads to single threads.

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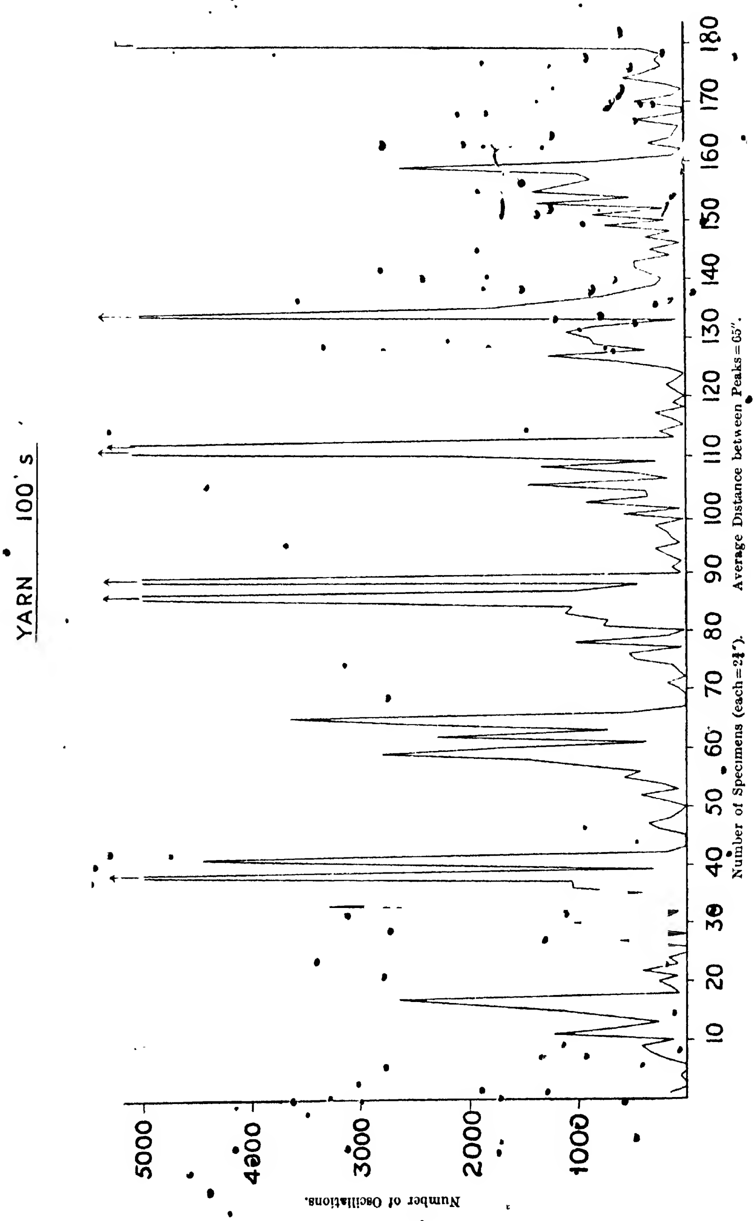

FIG. 8.

Periodicity of resistance to oscillating tensions in a mule yarn.

tions. Variations as great as these are found in ring yarns, though they are not periodic. This emphasises the importance of regularity in threads, since, in weaving, the warp threads have to stand several thousands of periodic stresses. To enable the warp threads to stand such stresses, they are sized, and experiments on the sized and unsized threads indicate the effectiveness of the cementing action of a given size on the fibres in the yarn.

Further information of great interest to the practical weaver relates

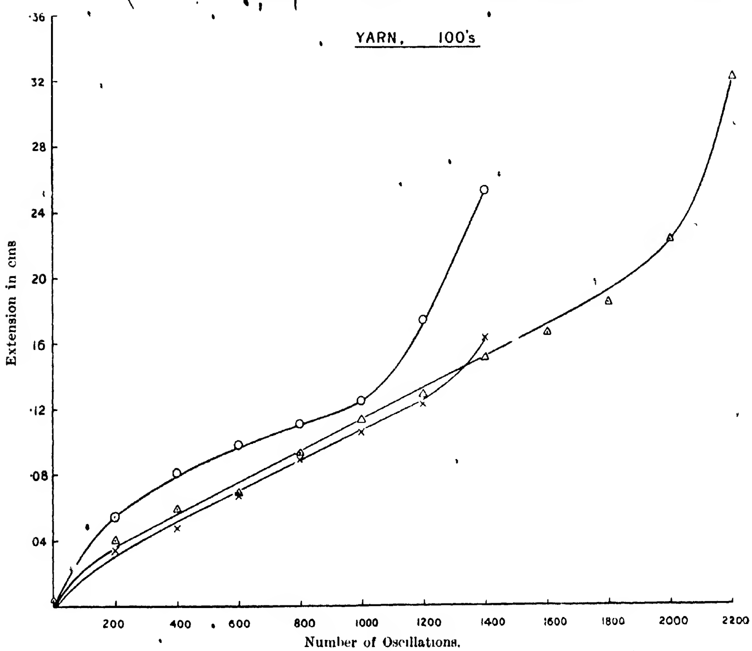

FIG. 9.

Extension curves under repeated oscillations.

to the degree of extensibility to which a thread may be subjected by such oscillatory stresses without breakage. Oscillation extension curves, Fig. 9, indicating how such threads extend at first rapidly, then less rapidly, and finally again more rapidly before rupture, have been obtained as the oscillation experiments proceed, by measuring on a cathetometer the increasing distances between the respective grips. Hysteresis effects have also been investigated.

Most of you will be aware of the similarity of work on elastic fatigue as it applies to metals and that here described. Again, I would like to emphasise, however, the variability of the material with which the textile physicist is concerned, and it must be borne in mind that in his

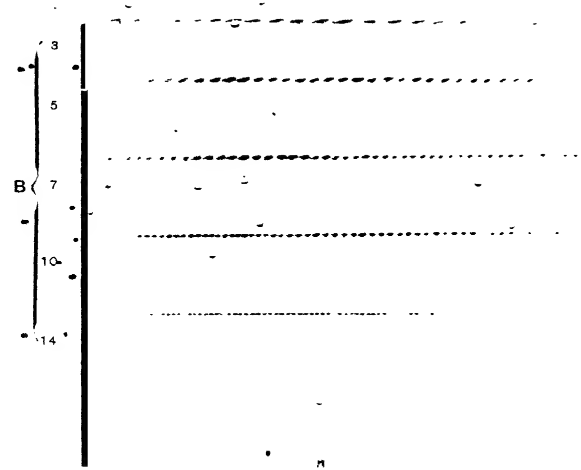

Fig. 10

Yarn 32s. A = single yarns; B = doubled yarns. (The numbers indicate doubling twist per inch.)

Photographic method of showing variation of lustre with doubling twist in the same yarn.

[Face p. 35]

case a specimen can never be reproduced, and, owing to the extreme variability of the material to be tested, it is often necessary to make very large numbers of tests in order to get a value representative of the bulk, which is the only information of real value to the spinner or manufacturer.

The general tendency of the cotton trade at present is towards the increased production of lustrous cotton goods, and the improvement of the lustre of cotton so that it may compete with the ever-increasing demand for artificial silk. From this demand numerous problems arise for the consideration of the physicist. Lustre on cotton may be produced in different ways, ranging from the ordinary simple mercerisation of the fabric (which, by the way, is claimed to be a chemical process although it is most probable that the effect depends really upon the change to a more symmetrical shape of the sections of the fibres) to the engraving of suitable patterns upon the surface of the fabric, a process called schreinering.

An investigation of the lustre of doubled yarns has recently been made. A doubled lustre yarn consists of two single yarns twisted together in the opposite direction to the twist put into the singles when they are spun. By means of a special photometer designed to measure the reflecting power of threads, it has been proved that the lustre of a doubled yarn depends upon the final position of the fibres from which it is spun. The position of the fibres with relation to the axis of the yarn is a function not only of the doubling twist but also of the twist of each of the single yarns, and there is therefore a definite relationship between the twist of the singles and the doubling twist which will lead to a maximum lustre. Further, any irregularity in the twist of the thread which causes it to depart from this relationship will cause a loss of lustre.

In Fig. 10 we have a view of a yarn whose doubling twist has been gradually increased. Graduated wedges have been inserted so that the reflecting power of the yarn is cut down as we pass from left to right of the figure. The more lustrous the yarn the greater distance to the right can we discern it, and there is a distinct indication of an optimum doubling twist giving rise to the maximum lustre. This is again confirmed by the photometer results shown in Fig. 11 (for a different yarn).

It has been stated that the lustre is a function of the doubling twist, and the latter has been examined by a modification of that used in measuring the regularity of single yarns. If the bottom cylindrical shoe, Fig. 4, is replaced by a fine wire, the doubling twists may be recorded as shown in Fig. 12. Each sharp peak on the photographs implies a half-doubling twist, and from the photographs we can readily obtain the maximum and minimum doubling twists along the yarn. Now, knowing the curve connecting the variation of lustre with doubling twist, Fig. 11, and the extreme ratios of the singles to the doubling twist, we can obtain the percentage variation of lustre along a sample of yarn. From the point of view of lustre, regularity of yarn is of vital importance, and the results obtained combined with those of the photometer have shown the necessity for more regular yarns. I might say that the lustre of raw materials and fabrics may be examined by a modified photometer.

In the finishing process called schreinering the fabric is raised to a suitable temperature and humidity and passed between heavy rollers weighing about 30 cwt., which are engraved with lines numbering from 150–300 per inch.. The fabric becomes marked in a way similar to a reflection grating, and this gives rise to a special lustre and finish. This finish is spoiled when the fabric is moistened, and the production of a permanent schreiner finish is a research problem of great importance.

It is true that the examples I have given refer mainly to cotton, but what I want to emphasise is that practically all the methods of testing which I have described, viz. measurements of elastic properties, sorting

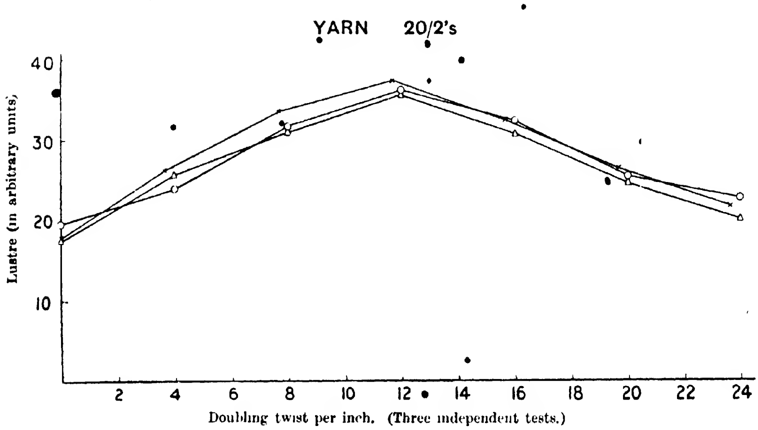

FIG. 11.

Photometric curves showing variation of lustre with doubling twist in the same yarn.

tests, regularity of the spun thread, the effects of variable stresses and fatigue, and the appearance of the finished fabrics, are purely physical measurements equally applicable, with suitable modifications, to all textile materials. There are many more problems which have been dealt with in this way, some of which are of too technical a character to be recounted here, and a far larger number, whose solution would be of immediate value to the textile trade, occur to one daily. A physical staff ten times the size of that now employed in textile research could readily be detailed for the solution of problems which are well worthy of investigation and which would furnish a rich reward.

Before I conclude, I would like to make one plea concerning publication of results. Much of the work now being done in textile research is of a more or less secret character, while much is of a fundamental scientific nature and is concerned mainly with the application of scientific method to some property of a material whose production is " well known to the

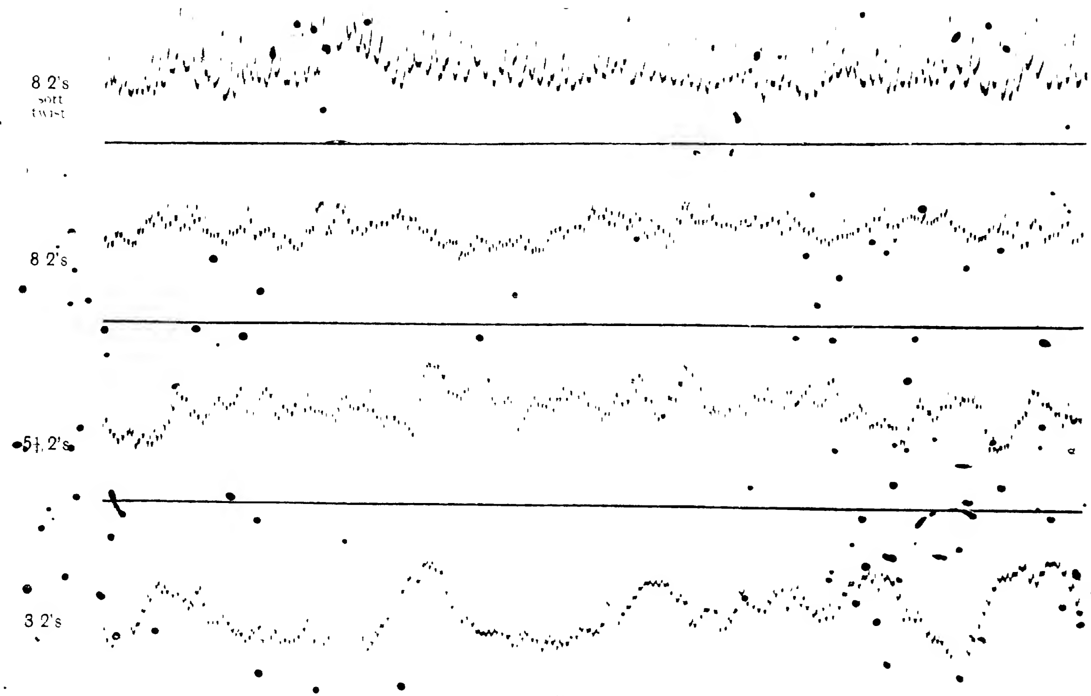

Fig. 12

Photographs of the regularity of doubling twists.

The trace is of the top surface of each yarn, each oscillation corresponding to a half doubling twist.

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"trade." A good deal of the latter work, though it may eventually lead to improved products, is published broadcast, and although such work is at least on a par with the scientific research which is done in other industries, I have looked in vain for mention of the progress of textile researches in our chief journals of scientific abstracts. Surely the march of science in the production of materials which, next to food, are the greatest commodities of mankind, is worthy of recognition in the fullest sense, and I look forward to a time in the near future when the applications of pure physics to textile research shall be recorded in the same way as are similar advances in the mechanical and electrical engineering industries.

LECTURE VI

THE PHYSICIST IN METALLURGY

DELIVERED IN THE

ROOMS OF THE CHEMICAL SOCIETY, LONDON

ON 6TH FEBRUARY 1924

BY

C. H. DESCH

D.Sc., Ph.D., F.R.S., F.I.C., F.Inst.P.

Professor of Metallurgy The University, Sheffield

The Hon. Sir CHARLES A. PARSONS, K.C.B., LL.D., F.R.S., President Inst.P.,

IN THE CHAIR

VI

ALTHOUGH every worker of metals from the earliest times has more or less unconsciously applied physical principles in the course of his labours, and although physics is historically an older science than chemistry, the conscious application of physical laws and methods to the practice of metallurgy is quite recent, more recent even than the control of metallurgical processes by the chemist. At the present day, a sound knowledge of physics is as essential to a trained metallurgist as a knowledge of chemistry, and year by year physical science becomes more prominent in the course of study of such young men as wish to undertake the control of metallurgical operations. Moreover, the research laboratories of the steel industry, which are rapidly growing in number and importance, require physicists as well as chemists on their staff, and this branch of work offers a good opening to a limited number of men trained in the use of physical apparatus and with imagination enough to attempt the solution of new problems in an unconventional way. It is necessary to insist on the need for imagination. The art of handling instruments is soon acquired, and under guidance intelligent but comparatively untrained assistants may learn to make accurate physical measurements as a matter of routine, but in a progressive works new problems present themselves daily to the worker who has the spirit of research, although they may have no existence for the unimaginative or unscientific mind, a type unfortunately too common in industry.

It is the rapid progress of engineering which is responsible for this demand on the activities of the physicist. The electrical industry, which has developed with such extraordinary rapidity in the last half-century, has called for metals and alloys having well-defined physical properties as well as that of mechanical strength, which was formerly the chief requisite. Copper and aluminium of high conductivity, resistance alloys of low conductivity and low temperature coefficient, transformer irons of high permeability, permanent magnet steels of high coercive force, alloys having a coefficient of thermal expansion close to that of glass, tungsten filaments which will bear heating to whiteness for long periods without becoming brittle, each represent a problem for the metallurgist, only to be solved by making the fullest use of modern physical knowledge. The influence of the mechanical engineer is not quite so obvious, but is as real and as important. So long as machines were heavy and ran at slow speeds there was a large margin of safety, and a small number of classes of steel, cast-iron, and non-ferrous alloys sufficed for practical purposes, but the advent of high speeds, combined with light construction, introduced new conditions. Let us consider, for example,

two steam engines, of the same horse-power and built at the same time, one being a pumping engine designed to run at 16 revolutions per minute, and the other a high-speed engine for a torpedo boat, running at 600 revolutions. The older cast and forged metals are adequate to the construction of the large pumping engine, but for the smaller quite different materials are required. The mysterious phenomena of fatigue have to be provided for, and the stresses, both steady and alternating, are greatly intensified. The contrast would be still more striking if we were to include an aeroplane engine, running at a very high speed and having the weight of every part cut down to a minimum. The steam turbine, which we owe to our distinguished President, has brought with it similar problems, together with others of its own, such as that of finding a metal which will resist the impact of strongly super-heated steam at high velocities without erosion. To meet these new requirements the metallurgical industry has been obliged to produce new alloys, the special steels and such non-ferrous alloys as those of nickel with copper or chromium. The new alloy steels require careful heat-treatment, that is, they must be heated to a predetermined and accurately known temperature, cooled at a definite rate, re-heated for tempering to an exact temperature, and so forth. Small deviations from the proper treatment may considerably impair the quality of the steel. The metallurgy of the non-ferrous alloys has lagged behind that of steel, but experience with the light aluminium alloys used in aircraft has proved that these also may be greatly improved by suitable heat-treatment, and the experience is likely to be general.

Other properties besides those of resistance to fatigue, abrasion, and erosion are required of metals by the engineer. The internal combustion engine requires cylinder castings which may be kept hot without undergoing permanent changes of form, and metals of high thermal conductivity for pistons. Here are further physical properties to be measured and investigated, and the field is clearly a wide one.

It has followed that the laboratories of a works manufacturing engineering materials of high class, say a Sheffield steel works making armament, motor and aeroplane steels, must be furnished with a wide range of physical instruments, and must have on its staff men capable of using them. We find, in fact, that the laboratories of the leading firms are very fully equipped with pyrometers, electrical and magnetic measuring instruments, and other implements of physical research, and that new instruments are frequently added as they are found to be essential.

A few concrete illustrations of the uses of physics in metallurgy may be given. It will only be necessary to mention a single point of contact between physics and the processes used in the treatment of ores. Metallic minerals are separated from the gangue or worthless non-metallic material by means of devices which make use of differences in physical properties. The varied jigs, concentrating tables, vanners, etc., separate minerals according to their specific gravity, whilst differences of magnetic quality and of behaviour in a strong electrostatic field are made use of in other forms of concentrating plant. The most interesting example, however,

is the method of flotation introduced in order to recover sulphides from the highly refractory tailings of Broken Hill, and now applied to some seventy million tons of ore, mostly of low grade, each year. This method consists in forming a froth on water and agitating with the crushed ore, when certain minerals are floated to the surface by the froth, and are removed by skimming, whilst others are wetted and sink. The sinking and floating have nothing to do with differences of density, some of the heaviest minerals being the most readily floated. By adding oils and varying the nature of the frothing agent, almost any desired separation may be brought about, often with almost exactly quantitative completeness.

Practice has outstripped theory in regard to flotation. The best conditions have been found by trial, and theoretical explanations have followed at a considerable interval. It is evident that the effects are due to differences of surface tension, but the surface tension at the boundary between a solid and a liquid is not easily determined, and the changes made by adding even small quantities of frothing agents to water are large. Mr. Edser has discussed this question very fully in the 4th Report of the Committee on Colloids, and his investigations, while showing how complex are the conditions, have made them intelligible, and a complete understanding of the process would be reached if we had accurate determinations of the angles of contact in every case, and of the alterations undergone by fresh surfaces of fracture on exposure to air or to reagents.

It is in the other department of metallurgy, that which deals with the heating, forging, hardening, and alloying of metals, that we find the most numerous and varied applications of physics. The measurement of temperature may be taken as a simple illustration. Modern metallurgical practice demands an ever-increasing accuracy in the control of furnace temperatures, the newer alloy steels in particular needing to be treated within very narrow limits if they are to be brought into their best physical and mechanical condition. For general use, the thermo-couple is the simplest and most convenient instrument, although for making a continuous record of the temperature of a furnace the resistance pyrometer has great advantages, and is often found in steel works. For temperatures above those that wires will withstand, optical or radiation pyrometers must be used, monochromatic instruments being preferable to those which measure total radiation. Pyrometers, useful as they are in skilled hands, are dangerous tools when used with insufficient understanding. The old-fashioned smith or tool-hardener, whose eye was trained by years of experience in a darkened workshop, could estimate the temperature of a mass of heated steel with an accuracy which would seem uncanny to a stranger, but his successor, probably his inferior in craftsmanship, who trusts to the readings of a pyrometer which may be in error, or which may have been set in a part of the furnace remote from the object being heated, sometimes fails to use his own judgment as a check on his instrument. Frequent calibration of thermo-couples is essential. The optical pyrometer, especially, may mislead operators who do not understand its limitations. A forging inside a uniformly

heated furnace, and observed through a small opening in the door, closely fulfils the conditions for a black body, but when the pyrometer is directed towards an ingot passing through the rolls, at one moment bare and at the next covered with a scale of oxide having an entirely different emissive power, most misleading indications may be obtained. Any one can use and read a pyrometer, but only a knowledge of physics will qualify a metallurgist to control the pyrometric equipment of a works and to ensure that the readings of the instruments have a real meaning.

Another illustration may be taken from the magnetic properties of metals. The steel-maker is directly interested in the magnetic properties of two classes of steel, namely, the material for permanent magnets and the soft steels of high permeability used for transformers. The importance of these two materials has justified the addition of magnetic instruments to many industrial laboratories, but these direct uses do not exhaust the technical importance of magnetic measurements. The susceptibility of a metal or alloy varies with the temperature, and the curve of variation may be used, as thermal curves are used, to study the temperatures of transformation (the so-called critical points) of steels, and hence their constitution. This method has been much used in Japan. For a given steel, again, the magnetic properties vary in a quite definite way with the thermal treatment, so that magnetic methods of determining the hardness of heat-treated steels are becoming common, and an instrument, the carbometer, has even been devised, by means of which the quantity of carbon in a furnace bath may be rapidly estimated by casting a slender bar of the steel in an iron mould and successively magnetising and demagnetising under certain conditions. Another interesting application originated in America. Rails, tubes, or other long objects of uniform section, may be surrounded by a solenoid, which travels along the length of the rail at a uniform rate. A test instrument, consisting of two small opposed coils connected with a galvanometer lies inside the solenoid. When the apparatus travels along a uniform rail no deflection is produced in the galvanometer, but an internal transverse crack is at once shown by disturbing the balance of the coils, causing a deflection. Wires and cables are tested in the same way, the solenoid travelling along the stretched object.

It is a little strange that, in spite of all the attention that has been given to the subject of magnetism, the magnetic theory of metals is still so imperfect. We are not yet in a position to predict the magnetic properties of a new alloy. Three striking examples may be mentioned. In 1898 F. Heusler discovered the remarkable alloys known by his name. Three metals of such feeble magnetic properties as copper, aluminium, and manganese, when melted together in certain proportions, form alloys which are comparable with iron in their magnetic qualities. The second example is even more striking. The magnetic properties of iron are almost destroyed when it is alloyed with 20 per cent. of nickel, and the higher nickel steels are often used when non-magnetic metals are required. Strangely enough, when the nickel is increased to 78·5 per cent., the carbon being very low, an alloy is obtained which has a permeability, in weak fields, much greater than that of pure iron, but the

alloy is magnetised nearly to saturation in the earth's field. There is nothing in the constitution of the alloys of iron and nickel to account for this remarkable property, which is confined to a narrow range of composition. Under the name of "Permalloy" this new steel is finding application in cable work.

On the other hand, cobalt was found by Honda to have a remarkable effect in improving the quality of permanent magnets, steels containing about 40 per cent. of cobalt having a surprisingly high coercive force. None of these effects could have been predicted from the constitutional diagrams of the respective alloys, and it is evident that magnetic theory is still very defective.

The metallurgist who is called on to investigate metals and alloys will find a knowledge of the methods of research used in physical laboratories of the greatest possible use to him. To be able to transform the measurement of some mechanical property into a simple determination of electrical resistance by means of a Wheatstone bridge, to know how to use a selenium cell for the control of temperature in a thermostat, may mean a great simplification of a piece of difficult experimental work. As an illustration of the use of physical principles in metallurgy in an unfamiliar way, I may mention a method devised in my laboratory by Mr. Cecil Handford, M.Met. The experimental problem was that of determining the load required to produce the first slip on crystal planes in a metallic test-piece under tension or compression. Microscopical observation of polished surfaces failed, as even with the most refined methods of illumination slip could not be detected until it had reached an advanced stage. The earliest slip-bands always evaded detection. Mr. Handford's method is based on the principle of Prof. Whiddington's ultra-micrometer. A flat polished surface of a test-piece is in contact with a thin sheet of mica, against which a brass plate is lightly clamped, the arrangement constituting an electrostatic condenser. When tension is applied to the test-piece, the surface remains plane so long as the extension is elastic, but plastic slip causes a minute ruffling of the surface, thrusting away the mica and brass plates, and thus diminishing the capacity of the condenser. The change is detected by means of a heterodyne arrangement of valves, producing an altered note in a telephone receiver, and the method proves to be much more sensitive than that of microscopical examination.

On the theoretical side, a remarkable feature of recent work in metallurgy has been the tendency to regard a metal as built up of atoms, and to study the properties of metals from the atomic point of view rather than in mass, as in thermo-dynamical treatment, for example.

The application of modern physical ideas to the study of metals is most fascinating, and whilst the results may often seem to the practical man to be of purely academic interest, nothing in metallurgy is more certain than that the academic knowledge of to-day will profoundly affect the industrial practice of to-morrow. Every one who has to manufacture metallic objects liable to be exposed to conditions of rapidly varying stress would gain by a knowledge of the internal changes in solids that lead to what we know as failure by fatigue. Mere workshop tests,

even when carried on over long periods and with the use of specially devised machines, leave the subject in great obscurity. The microscope brings much new knowledge, but it seems likely that the revelation of the internal structure of crystals by the method of X-ray analysis, which is expanding so rapidly and so marvellously, will prove of still higher value. This method, combined with the new knowledge of the internal electronic structure of the atom, is teaching the nature of cohesion and explaining the "directed" quality of that important property. It has even been found possible, in Dr. A. A. Griffith's experiments with silica glass, to obtain under the proper conditions a cohesive strength far in excess of that found in ordinary practice, and corresponding closely with the value calculated on theoretical grounds. Dr. Rosenhain, in his recent "Sorby" Lecture, has made this fact the basis of a vision of future metals, of enormously greater mechanical strength than those which we know, although built up of the same atoms. Whether such a structure can be rendered stable is an attractive problem for the future.

The properties of the crystalline space-lattice have already ceased to be of merely academic interest, and X-ray analysis is proving of value to the steel manufacturer. The question as to which of the allotropic modifications of iron is present in hardened steel has been the cause of much controversy, and has only been settled by the X-ray experiments of Westgren, which showed clearly that the α-space lattice was present as in the slowly cooled steels, so that the increased hardness could only be due to the presence of the carbon atoms, producing distortion of the lattice. In a similar way, the supposed resolution of the β solid solution in brasses into two constituents on cooling, as to which the thermal and microscopical evidence was conflicting, has been finally disproved by the X-ray measurements of Owen and Preston.

It has been found possible to obtain single crystals of certain metals of such large size that their mechanical properties may be determined with the aid of an ordinary testing machine. This has been done in two ways. Professor Carpenter and Miss Elam have found that by straining pure aluminium to a certain critical extent and then annealing the strained specimens, some of the crystals may grow to such an extent that an entire specimen may come to consist of a single crystal. The exact nature of the deformation of a single crystal of aluminium has been determined quantitatively by Professor Taylor and Miss Elam. On the other hand, by introducing a nucleus into a molten metal and raising the crystal at a rate just equal to the velocity of crystallisation, large single crystals of several metals have been obtained. The process of deformation is particularly illuminating in the case of zinc, studied by Polanyi, as slip is almost entirely limited to the basal plane of the hexagonal crystal.

There is at least one technical application of the process of growing large crystals. The manufacture of electric incandescent lamps is troubled by the tendency of tungsten filaments to become coarse-grained when heated for a long time. When the grains become so large as to extend over the entire cross-section of the filament, "off-setting" may occur,

and the filament may break. One way of preventing such growth is by interposing mechanical obstacles, in the shape of small particles of thorium oxide, so that the crystal grains remain small. The alternative is to use filaments composed of a single crystal, thus avoiding grain boundaries altogether. This plan is actually in use, and proves to be successful.

The properties of large crystals have a special interest and they may prove to be technically important. They have a low elastic limit but a definite fatigue range, and a remarkably high ductility, even when the metal in the form of an aggregate of grains is brittle, as zinc. This ductility may well be utilised technically in the near future. Moreover, the tungsten filaments composed of a single crystal are free from elastic after-working, and therefore lend themselves to use as galvanometer suspensions. In fact, the complete elimination of that puzzling factor in scientific metallurgy, the inter-crystalline boundary, may lead to important practical consequences.

The electrical engineer has long found entrance to the metallurgical industries, and electric furnaces and electrically driven rolling mills are among the commonplaces of steel manufacture, but even in this field there is room for the physicist who is able to introduce new ideas. One of the most recent developments in the melting of metals is the use of the high-frequency induction furnace, by means of which a crucible charge of steel or other metal of high melting point may be rapidly melted without contact with contaminating gases or fuel, and if necessary in a good vacuum. As a laboratory apparatus this furnace has immense advantages, and it is already used in several manufacturing operations. The possibilities of the thermionic valve in metallurgical work are great, but have as yet been little considered.

Apart from the use of optical pyrometers, and of the microscope, a study in itself, optical principles find few applications to the metal industries, but that such applications are possible may be illustrated by mentioning the increased resolution of fine surface detail recently observed in illumination by polarised light, and the measurement of reflectivity as a means of determining quantitatively the effect of different abrasives in the grinding and polishing of metals, and also of following the process of tarnishing when polished metallic surfaces are exposed to the atmosphere of towns.

These few examples may show how large is the field for a scientifically trained man, having a good knowledge of the principles of physics and practical skill in the methods of research, when he enters the metallurgical industry, and also how important it is that the student of metallurgy should have a good grounding in physics. The technical side of metallurgical science and practice is so complex that an honours' graduate in pure science may find himself at a loss when he enters a steel works or some similar establishment, and there is little doubt that the ideal university training for such a purpose is a degree course in pure science followed by a shorter specialised course in metallurgy, perhaps leading to a higher degree. This arrangement has proved successful in practice, and should appeal to the physicist as well as to the chemist, both of

whom are needed in metallurgical industry. Each should have sufficient acquaintance with the other's special branch of science to understand his methods and difficulties, and each should have that breadth of mind which is necessary to appreciate the difficulties of the experienced but probably not scientifically trained practical man—melting-shop or rolling-mill manager or works chemist. The training of each should be such as to bring about mutual respect among all of them, and so facilitate that co-operation which is essential to the future success of industry.